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a Practical Procedure for Introduction of an Air Terminal Device in CFD Calculation

Nielsen, Peter Vilhelm

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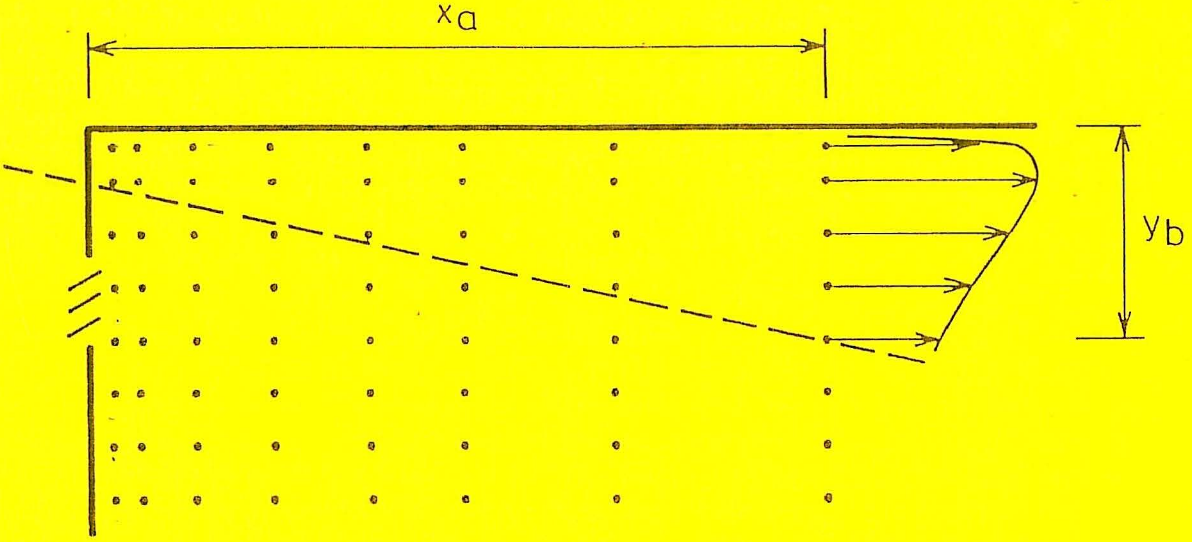

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The Prescribed Velocity Method - a Practical Procedure for Introduction of an Air Terminal Device in CFD Calculation

by

Peter V. Nielsen
Aalborg University

Abstract

The velocity level in a room ventilated by jet ventilation is strongly influenced by the supply conditions. The momentum flow in the supply jets controls the air movement in the room and, therefore, it is very important that the inlet conditions and the numerical method can generate a satisfactory description of this momentum flow. The Prescribed Velocity Method is a practical method for the description of an Air Terminal Device which will save grid points close to the opening and ensure the right level of the momentum flow.

Introduction

Figure 1 shows the decay of the maximum velocity in the flow that runs along the ceiling in a room with two-dimensional recirculating air movement. The velocity level obtained by two different inlet conditions, corresponding to two different supply openings, is retained in the flow along the ceiling. The difference in the velocity level will be retained in the occupied zone as well. A satisfactory description of the inlet conditions is, therefore, very important for the prediction of the flow in the whole room.

Figure 1 also shows that the velocity decay below the ceiling corresponds to the conditions in a wall jet, except close to the end wall opposite the supply opening. This means that the air movement below the ceiling can be expressed by parabolic equations, although the flow as a whole is recirculating and, therefore, described by elliptic equations. This strong upstream influence in the first part of the flow is the background for the wall jet description of boundary conditions for supply openings discussed in this paper.

The momentum flow in the wall jet below the ceiling controls the air movement in a room. For example, the maximum velocity in the occupied zone is proportional to the inlet velocity multiplied by the square root of the supply area, which expresses the square root of the supply momentum flow. Therefore, it is very important that the inlet conditions and the numerical method produce a satisfactory description of the momentum flow.

The supply momentum flow from diffusers depends on small details in the design. This means that a numerical prediction method should be able to handle small details in the order of a few millimetres to room dimensions of many metres. This wide range of geometry necessitates the use of many grid points and demands, therefore, a large computer or a procedure which can reduce the number of grid points.

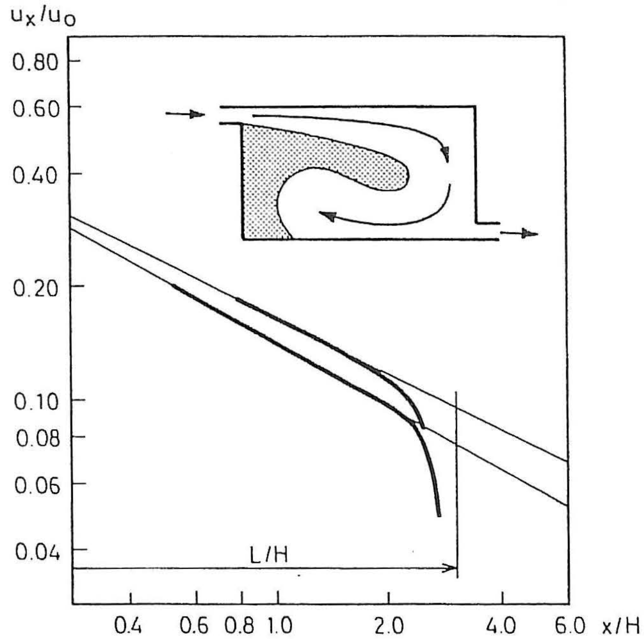

Figure 1. Velocity decay in the flow along the ceiling in a room. Predictions are shown for two different diffusers with the same slot height, h/H = 0.0015 and L/H = 3, where h, H and L are slot height, room height and room length, respectively.

The Prescribed Velocity Method

The Prescribed Velocity Method (PV-method) has been successfully used in the numerical prediction of room air movement. The method is described by the author for the first time in Gosman et al. (1980). Figure 2 shows the details of the method. The inlet profiles are given as boundary conditions at the diffuser in the usual way, although they are represented only by a few grid points. All the variables - except the velocities u and w - are predicted in a volume close to the diffuser as well as in the rest of the room. The velocities u and w are prescribed in the volume in front of the diffuser as the analytical values obtained for a wall jet from the diffuser, or they are given as measured values in front of the diffuser.

The velocity distribution for a wall jet (or a free jet) generated by different commercial diffusers can be obtained from diffuser catalogues or design guide books as ASHRAE Fundamental (1997) and from text books as e.g. Awbi (1991), Rajaratnam (1976), Etheridge and Sandberg (1996) and Nielsen (1995).

It is sufficient to prescribe the u-velocity when the supply jet is a two-dimensional jet, a circular jet or a bluff wall jet.

The prescribed velocity volume is surrounded by two vertical surfaces a_1 and a_2 perpendicular to the jet flow, a horizontal surface b between the jet and the surrounding flow and two vertical surfaces c_1 and c_2 parallel to the flow in the outer region of the jet profile.

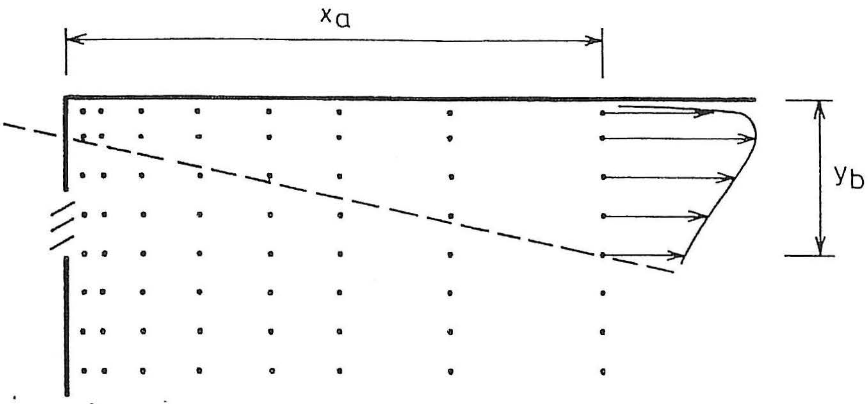

Figure 2. Prescribed velocity field close to the supply opening. The two distances indicate the location of surfaces a_2 and b.

The supply opening is often located in the symmetry plane of the room. If it is assumed that the flow is symmetrical it is allowed to make a prediction of the flow in only one half of the room. z_{c1} will in this case be equal to $-z_{c2}$. The prescribed velocity volume is surrounded by the surfaces a_1, a_2, b, c_1 and the symmetry plane $(z = 0.0)$.

The considerations to be made with regard to size and location of surfaces a_2 and b, as well as the number of grid points are the same considerations as in the *Box Method*, see Nielsen (1989, 1992 and 1997).

The following procedure is used by the PV-scheme: All the variables u, v, w, p, k and ε are predicted by iterations in the *whole* room including the small volume (a_1, a_2, b, c_1, c_2) close to the diffuser. The velocities u and w are updated in the volume after each iteration to the analytical values. Other variables in the volume (a_1, a_2, b, c_1, c_2) as e.g. turbulent kinetic energy k are therefore obtained as a solution of the turbulence transport equations combined with the corrected u and w velocity profiles.

The PV-method is easy to use because it is only necessary to specify the u and w profiles in the volume while the variables v, p, k and ε are predicted. It is necessary to prescribe the temperature distribution and the contaminant distribution in the case of non-isothermal flow and flow with contaminant distribution.

Results obtained by the Prescribed Velocity Method

Figure 3 shows the velocity distribution in a room with a jet issued from a circular opening with a small diameter compared to other room dimensions. The measurements are made by a Pitot-tube and they are made in scale model experiments by Blum (1956).

The predicted velocity distribution is based on the PV-method with prescribed downstream u-profiles at $x/H = 1.14$, see figure 3. The decay of the maximum velocity is slightly underpredicted with an associated difference of 5 percent in the centreline at $x/H = 2.54$. However, the general agreement is satisfactory, the discrepancies, for example, are below 1 percent of the maximum flow velocity in the reverse flow. The measurements and predictions are also shown in figure 4. The velocity u_{xp} is the maximum velocity in the wall jet which flows along the surfaces down into the occupant zone, and x_p is the distance from the supply opening along the perimeter of the room, see the figure 4a. Figure 4b shows the velocity decay u_{xp} / u_o versus x_p / H in the room shown in figure 3. It is obvious that a direct prediction of the velocity distribution without use of the Prescribed Velocity Method leads to poor agreement with the measured data. It is - today - possible to make good predictions of the flow from a single circular opening, and the discrepancies shown in figure 4b are to some extent the result of a coarse grid distribution, see Gosman et al. (1980).

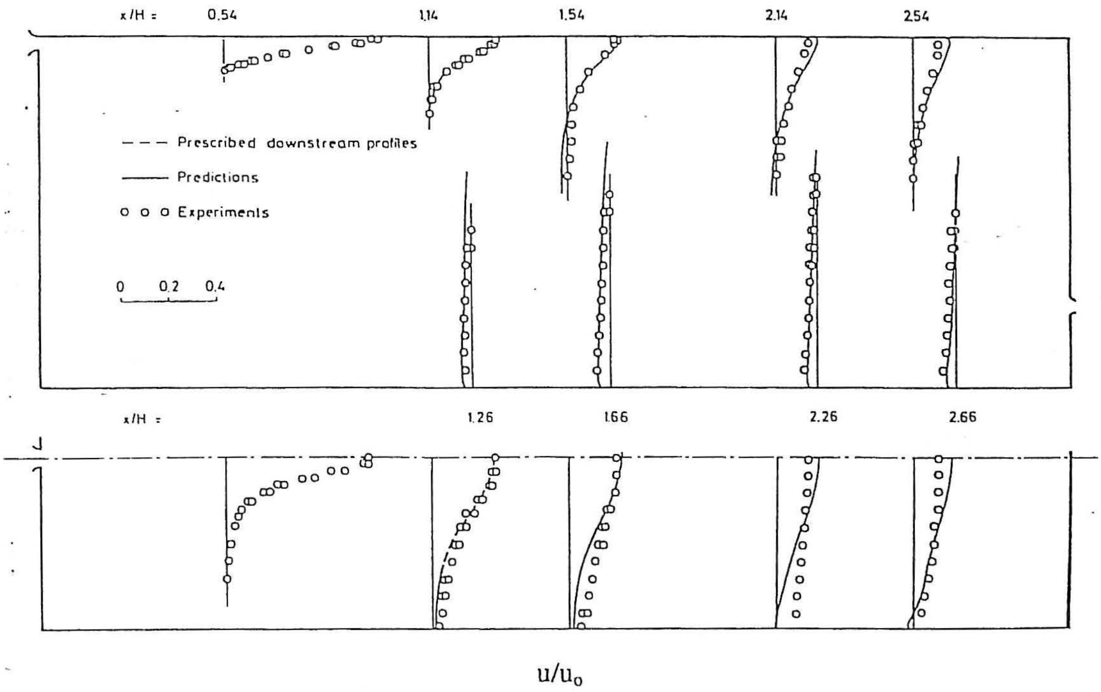

Figure 3. Measurements and predictions of velocity profiles in a room with a circular nozzle placed in the middle plane of the room close to the ceiling. The upper figure shows a vertical section, and the lower figure shows a horizontal section through the symmetry line of the nozzle. $L / H = 3.0$, $W / H = 1.0$ and $Re = 93000$.

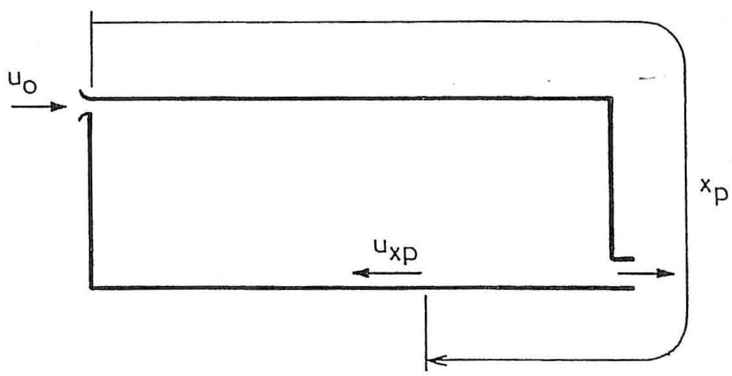

Figure 4a. Definition of the length x_p.

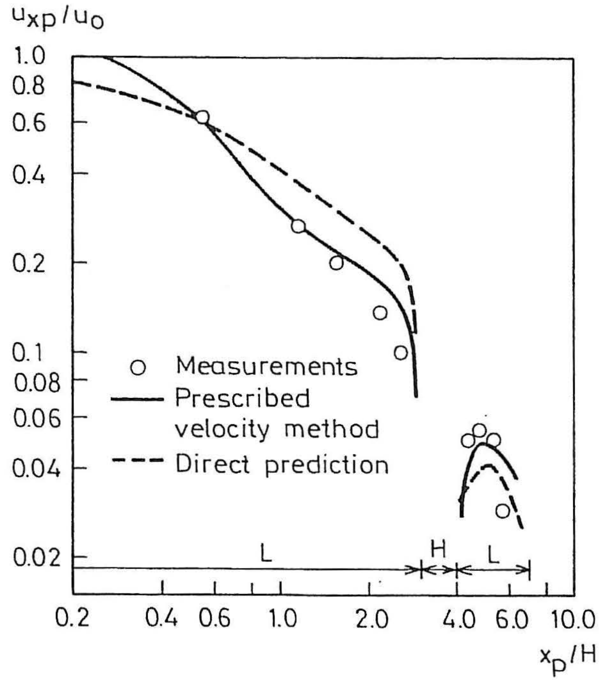

Figure 4b. Measured and calculated maximum velocity around the perimeter of a room. $L/H = 3.0$, $W/H = 1.0$ and $Re = 93000$.

A complicated supply geometry was used in the IEA Annex 20 work to ensure that the generation of the boundary conditions was demanding, as it will be for many commercial diffusers, see Lemaire (1993). Several of the IEA participants used the Prescribed Velocity Method with success in this situation. Figure 5 shows a close-up of the IEA Annex 20 diffuser which consists of 84 nozzles arranged in three horizontal rows. The diffuser is located 0.2 m below the ceiling, and the nozzles are adjusted to an angle of 40° towards the ceiling.

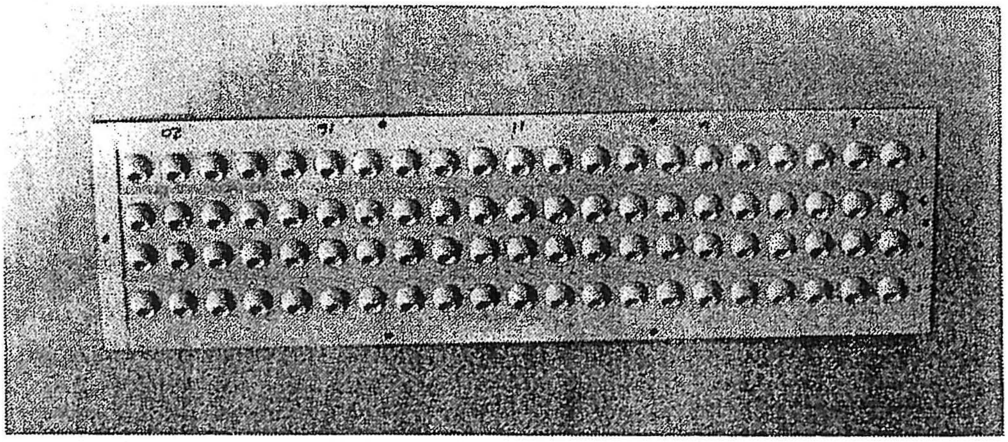

Figure 5. Close-up of the IEA Annex 20 inlet device.

Results obtained by Skovgaard and Nielsen (1991) are shown in figure 6. The maximum velocity in the occupied zone of the standard IEA 3D room is shown as a function of the air change rate. The most obvious way to simulate an inlet opening is to replace the actual diffuser by a less complicated geometry that supplies the same momentum flow to the room. The 84 nozzles in the IEA diffuser are replaced by a rectangular opening with the same supply area, aspect, ratio and velocity direction as the actual diffuser. This method is called the simplified boundary condition method. Figure 6 shows that simplified boundary conditions will overestimate the velocity in the occupied zone by 40%.

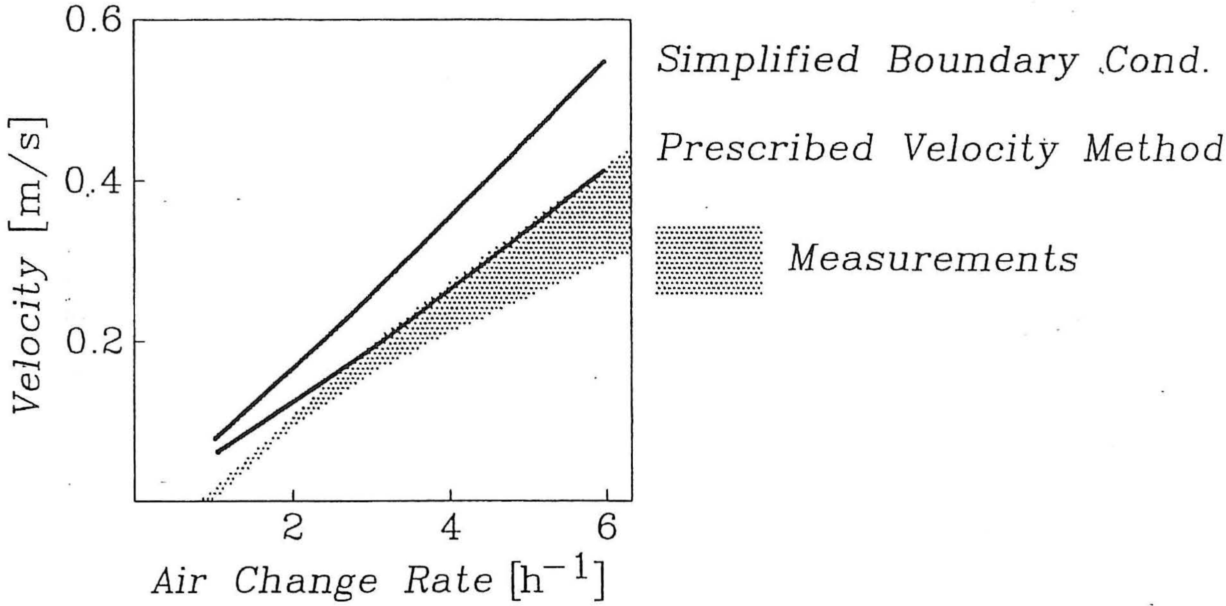

Figure 6. Maximum velocity in the occupied zone of the IEA Annex 20 room versus air change rates. Measurements and predictions with and without the Prescribed Velocity Method.

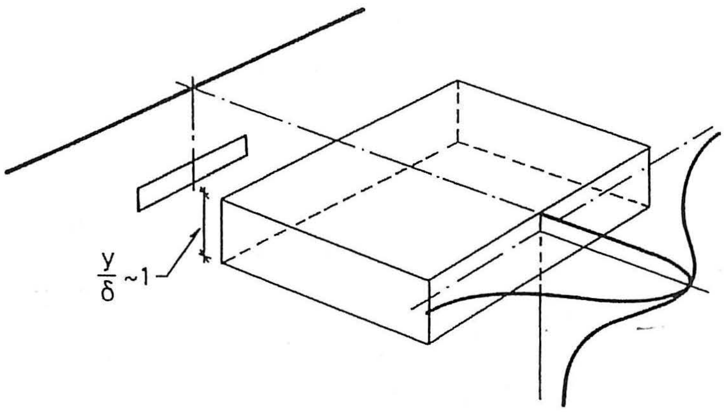

Figure 7. The location of the prescribed velocity volume in front of the diffuser, Skovgaard (1991).

The Prescribed Velocity Method is illustrated in figure 7. The boundary conditions at the opening are given as the simplified boundary conditions where the mass flow and the momentum flow correspond to the required air change rate. The fulfilment of the detailed radial momentum flow is obtained by prescribed boundary conditions in the imaginary volume $(a_1,\ a_2,\ b,\ c_1, c_2)$ in front of the diffuser at a location where a wall jet flow of parabolic nature is established, see figure 7.

The maximum velocity u_r in the semiradial jet inside the control volume can be given by

$$u_r = K(\theta) u_o \frac{\sqrt{a_o}}{x + x_o} \qquad (1)$$

where u_o is the supply velocity, a_o the supply area (given as a function of air flow rate) and $x + x_o$ the distance from the virtual origin of the wall jet flow. $K(\theta)$ is a characteristic function for the diffuser and diffuser installation. Figure 8 shows $K(\theta)$ versus the direction in the horizontal plane θ found by experiments.

Two components of the maximum wall jet velocity are given by

$$u_x = \cos\theta \; u_r \qquad (2)$$

$$w_z = \sin\theta \; u_r \qquad (3)$$

and the u and w components in the prescribed volume are found from u_x, w_z and from the assumption of the self-similar wall jet profiles and linear growth of the jet length scale.

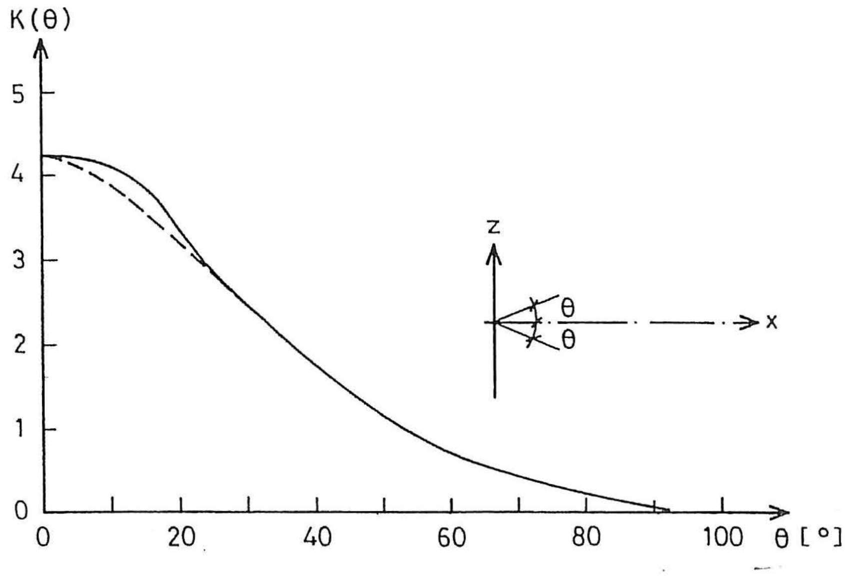

Figure 8. Diffuser coefficient $K(\theta)$ versus direction θ.

The use of the Prescribed Velocity Method improves the prediction of the maximum velocity in the occupied zone, see figure 6, and the results are in agreement with the measurements made by the participants in the IEA project, see Skovgaard and Nielsen (1991).

A new investigation of the inlet boundary conditions for numerical prediction of air flow in livestock buildings shows that it is possible to improve the prediction of the maximum velocity in the occupied zone from a 27% underestimate to an underestimate of only 9% by use of the PV-method, see Svidt (1994).

List of symbols

a_1, a_2	
b	
c_1, c_2	Control surfaces
a_o	Supply area
d	Diameter of supply opening
h	Effective height of supply opening
H	Height of room
k	Turbulent kinetic energy
$K(\theta)$	Velocity decay coefficient for wall jet
L	Length of room
p	Pressure
Re	Reynolds number
u	Velocity in x-direction
u_x	Maximum velocity in wall jet (x-direction)
u_o	Supply velocity
u_r	Maximum velocity in wall jet (θ-direction)
u_{xp}	Maximum velocity in wall jet
v	Velocity in y-direction
w	Velocity in z-direction
w_z	Maximum velocity in wall jet (x-direction)
W	Width of room
x_{a1}, x_{a2}	
y_b	
z_{c1}, z_{c2}	Control surface co-ordinates
x	Co-ordinate
x_o	Distance to virtual origin of jet
x_p	Length along perimeter of the room
y	Co-ordinate
z	Co-ordinate
ε	Dissipation of turbulent kinetic energy
θ	Direction of radial wall jet flow

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Appendix A

Fortran listing of elements of the Prescribed Velocity Method (Gosman et al. 1980).

```
C
      NAMELIST /NLIST9/ IWJ2,JWJ2,KWJ1,KWJ2
      NAMELIST /NLIS10/ CWIN,ZZEROW,CDELX,CDELY,ZZEROX,ZZEROY
C
C
CHAPTER  1  1  1  1  1  1  1  SLENDER WALL JET  1  1  1  1  1  1  1
C
C
C     THIS CHAPTER DESCRIBES THE INLET CONDITIONS FOR THE MEASUREMENTS
C     IN REPORT FS/77/13, IMPERIAL COLLEGE, MECH. ENG. DEP.,1977.
C
C               SIMILAR VERTICAL PROFILES FOR A SLENDER WALL JET OUTSIDE
C               Y=WSMALL, SEE XXXX, ARE IN ACCORDANCE WITH SFORZA, AIAA
C               JOURNAL VOL 8 NO 2.
C
C
      ENTRY WJIC1
C
C-----READ COORDINATES INTO COM5
      READ(5,NLIST9)
C     NAMELIST CONTROL
      WRITE(6,NLIST9)
C-----WALL JET PROFILE AT K=4
      W(1,1,4)=1.68
      W(2,1,4)=1.73
      W(3,1,4)=1.66
      W(4,1,4)=1.34
      W(5,1,4)=1.1
      W(6,1,4)=0.7
      W(7,1,4)=0.32
      W(2,1,4)=1.73
      W(2,2,4)=1.58
      W(2,3,4)=1.16
      W(2,4,4)=0.78
      W(2,5,4)=0.52
      W(2,6,4)=0.39
      W(2,7,4)=0.3
      W(2,8,4)=0.26
C-----GENERATION OF HALF VELOCITY LENGTH XW2(J)
      K=4
      DO 800 J=2,8
      XW2=0.08429-Y(J)*0.08573
C-----GENERATION OF VERTICAL PROFILES AT ZW=1.0
C     REICHARDT-PROFILE (SEE THESIS OF URBACH, TH AACHEN)
      DO 800 I=2,7
      ETAX=(X(I)-X(2))/XW2
      WWJ(I,J,K)=W(2,J,K)*EXP(-0.693*ETAX*ETAX)
  800 CONTINUE
C-----NEAR WALL VALUE SYMMETRIC AROUND MAX VELOCITY
      DO 802 J=2,8
  802 WWJ(1,J,K)=WWJ(3,J,K)
C-----WALL JET VALUES WWJ(I,J,K) TRANSFERRED TO VELOCITY FIELD
      DO 804 J=2,8
      DO 804 I=1,7
  804 W(I,J,K)=WWJ(I,J,K)
C-----MEASURED VELOCITY PROFILE TRANSFERRED TO WWJ(I,J,K)
      DO 806 I=1,7
  806 WWJ(I,1,K)=W(I,1,K)
      RETURN
C
```

```
C
CHAPTER  2  2  2  2  2  2  2  BLUFF WALL JET  2  2  2  2  2  2
C
C
C     THE WALL JET AREA IS GENERATED FROM THE FOLLOWING ASSUMPTIONS
C
C               DECAY OF PEAK VELOCITY WMAX FROM THE FORMULA
C               IN LINE XXXX
C
C               GROWTH OF DELTA IN X-DIRECTION AND IN Y-DIRECTION
C               FROM THE FORMULAS IN LINE XXXX AND XXXX
C
C               REICHARDT-PROFILE IS ASSUMED FOR THE CENTER LINE
C               VELOCITY WCEN, SEE LINE XXXX
C
C               THE DISTANCE XCWMAX IS IN ACCORDANCE WITH 2D-THEORY,
C               SEE THE PAPER OF RAJATNAM AND LINE XXXX
C
C               SIMILAR HORIZONTAL PROFILES ARE ASSUMED IN A BLUFF
C               WALL JET, LINE XXXX, AND THE FORMULA IN LINE XXXX
C               ARE RECOMMENDED FOR ALL X UP TO X(IWJ2), SEE
C               RAJARATNAM: TURBULENT JETS
C
C               THE REICHARDT-PROFILE IS DESCRIBED IN THE THESIS
C               OF URBACH, TH AAHCEN 1971.
C
C     THE GENERAL BLUFF WALL JET ASSUMPTIONS ARE USED TO GENERATE
C     THE INLET CONDITIONS FOR THE MEASUREMENTS DESCRIBED BY
C     BLUM, TH AACHEN 1956
C
C
      ENTRY WJBLUF
C
C-----READ COORDINATES AND DATA FOR WALL JET
C     ALL LENGTH SHOULD BE GIVEN DIMENSIONLESS BY DIVIDING
C     BY THE ROOM HEIGHT
      READ(5,NLIST9)
      READ(5,NLIS10)
C     NAMELIST CONTROL
      WRITE(6,NLIST9)
      WRITE(6,NLIS10)
C-----SET VELOCITY TO ZERO
      DO 100 K=1,NKM1
      DO 100 J=1,NJ
      DO 100 I=1,NI
 100  WWJ(I,J,K)=0.0
C-----DISTANCE TO VELOCITIES (NORMALLY PRODUCED IN INIT)
      DO 105 K=KWJ1,KWJ2
 105  ZW(K)=0.5*(Z(K)+Z(K+1))
C-----GENERATE WWJ(I,J,K) IN WALL JET AREA
      DO 110 K=KWJ1,KWJ2
      WMAX=WIN*CWIN*SQRT(HSMALL*2.*WSMALL)/(ZW(K)+ZZEROW)
      DELTAX=CDELX*(ZW(K)+ZZEROX)
      DELTAY=CDELY*(ZW(K)+ZZEROY)
      XCWMAX=0.16*DELTAX
      DO 110 I=1,IWJ2
      ETAX=ABS(X(I)-XCWMAX)/(DELTAX-XCWMAX)
      WCEN=WMAX*EXP(-0.693*ETAX*ETAX)
      DO 110 J=1,JWJ2
      ETAY=Y(J)/DELTAY
      WWJ(I,J,K)=WCEN*EXP(-0.693*ETAY*ETAY)
 110  CONTINUE
      RETURN
C
C
CHAPTER  3  3  3  3  3  3  BLUFF WALL JET (UNDEVELOPED ZONE)  3  3  3
C
```

```
C                                                                         00001580
C      THIS CHAPTER DESCRIBES THE INLET CONDITIONS FOR THE MEASUREMENTS   00001590
C      IN REPORT FS/78/14, IMPERIAL COLLEGE, MECH. ENG. DEP.,1978.        00001600
C                                                                         00001610
C                SIMILAR HORIZONTAL PROFILES ARE ASSUMED, SEE             00001620
C                RAJARATNAM: TURBULENT JETS                               00001630
C                                                                         00001640
C                HALF VELOCITY LENGTH, DELTAY, IS ASSUMED TO BE           00001650
C                CONSTANT, SEE LINE XXXX                                  00001660
C                                                                         00001670
C                REICHARDT-PROFILE IS ASSUMED FOR THE CENTER PLANE        00001680
C                VELOCITY WCEN, SEE LINE XXXX, AND FOR THE HORIZONTAL     00001690
C                PROFILES, SEE LINE XXXX                                  00001700
C                                                                         00001710
C                                                                         00001720
      ENTRY WJIC2                                                         00001730
C                                                                         00001740
C-----READ COORDINATES AND DATA FOR WALL JET                              00001750
C     ALL LENGTH SHOULD BE GIVEN DIMENSIONLESS                            00001760
C     BY DIVIDING BY THE ROOM HEIGHT                                      00001770
      READ(5,NLIST9)                                                      00001780
C     NAMELIST CONTROL                                                    00001790
      WRITE(6,NLIST9)                                                     00001800
C-----SET VELOCITY TO ZERO                                                00001810
      DO 200 K=1,NKM1                                                     00001820
      DO 200 J=1,NJ                                                       00001830
      DO 200 I=1,NI                                                       00001840
  200 WWJ(I,J,K)=0.0                                                      00001850
C-----DATA FOR CENTER PLANE VELOCITY                                      00001860
      DELTAX=0.125                                                        00001870
      XCWMAX=0.05                                                         00001880
      WMAX=0.75*WIN                                                       00001890
C-----DATA FOR HORIZONTAL PROFILES                                        00001900
      DELTAY=0.12                                                         00001910
C-----GENERATION OF WWJ(I,J,K) IN WALL JET AREA                           00001920
      K=KWJ2                                                              00001930
      DO 210 I=1,IWJ2                                                     00001940
      ETAX=ABS(X(I)-XCWMAX)/(DELTAX-XCWMAX)                               00001950
      WCEN=WMAX*EXP(-0.693*ETAX*ETAX)                                     00001960
      DO 210 J=1,JWJ2                                                     00001970
      ETAY=Y(J)/DELTAY                                                    00001980
      WWJ(I,J,K)=WCEN*EXP(-0.693*ETAY*ETAY)                               00001990
  210 CONTINUE                                                            00002000
      RETURN                                                              00002010
      END                                                                 00002020
```

The geometry in the program has its origin in the intersection of the symmetry plane, the wall with diffuser and the ceiling. The z-axis is parallel to the ceiling in the direction of the flow from the supply opening. The x-axis is directed downward. The y-axis is horizontal and perpendicular to the flow from the supply opening.

Chapter 1 in the Fortran program gives the prescribed velocity distribution in a single surface a_2 as used in the predictions shown in figure 3. Data for two profiles based on measurements are given in the lines 580 to 730. The length scale is calculated from measurements in the lines 750 - 770. The remaining wall jet at surface a_2 is based on fully developed profiles. The wall jet profiles WWJ (I, J, K) are transformed into the solution domain W(I, J, K) in the lines 870 to 900.

Chapter 2 shows the Prescribed Velocity Method described in a volume $(a_1,\ a_2,\ b,\ c_1)$ based on analytical values from relevant text books or from diffuser catalogues.

The prescribed velocity volume is defined by the grid numbers (I, J, K_1, K_2) ~ (IWJ2, JWJ2, KWJ1 and KWJ2). The velocity distribution WWJ (I, J, K) is generated from analytical wall jet equations and self-similar velocity profiles in the lines 1410 to 1510.

Chapter 3 shows a version of the PV-method where the prescribed velocity distribution is given in a single surface , a_2, corresponding to K = KWJ2. The velocity distribution is calculated from the analytical wall jet equations.

Fortran listing of the velocity update in the main program.

```
C-----INITIAL WALL JET ASSUMPTIONS                                         00005800
C       PASS WALL JET AREA WHEN FLOW IS DEFINED FROM OPENING               00005802
        IF(IWJET.EQ.0) GO TO 310                                           00005804
C       PASS CALCULATIONS OUTSIDE WALL JET AREA                            00005806
        IF(K.LT.KWJ1.OR.K.GT.KWJ2) GO TO 310                               00005808
C-----WALL JET VALUES WWJ(I,J,K) TRANSFERRED TO VELOCITY FIELD              00005820
        DO 314 I=1,IWJ2                                                    00005830
        DO 314 J=1,JWJ2                                                    00005840
 314    W(I,J,K)=WWJ(I,J,K)                                                00005850
C-----MODIFICATION ON SU(I,J) AND SP(I,J)                                   00005860
        DO 312 I=1,IWJ2                                                    00005870
        DO 312 J=1,JWJ2                                                    00005880
        SU(I,J)=GREAT*W(I,J,K)                                             00005890
 312    SP(I,J)=-GREAT                                                     00005900
 310    CONTINUE                                                           00005910
        RETURN                                                             00005920
        END                                                                00005930
```

The program works with both the simplified boundary conditions for IWJET = 0 (line 5804) and the PV-method for IWJET = 1. The wall jet values are transferred to the velocity field and updated in the lines 5820 to 5930.